

Development of Flywheel Energy system

Presented by

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and

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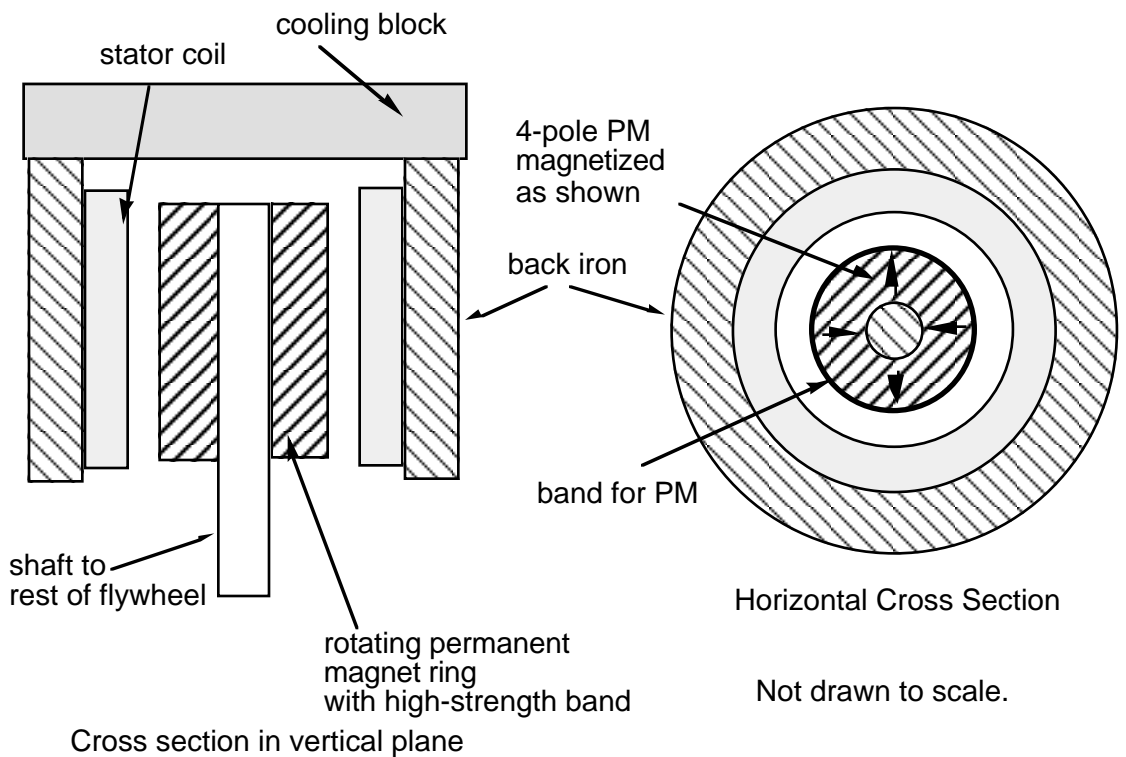
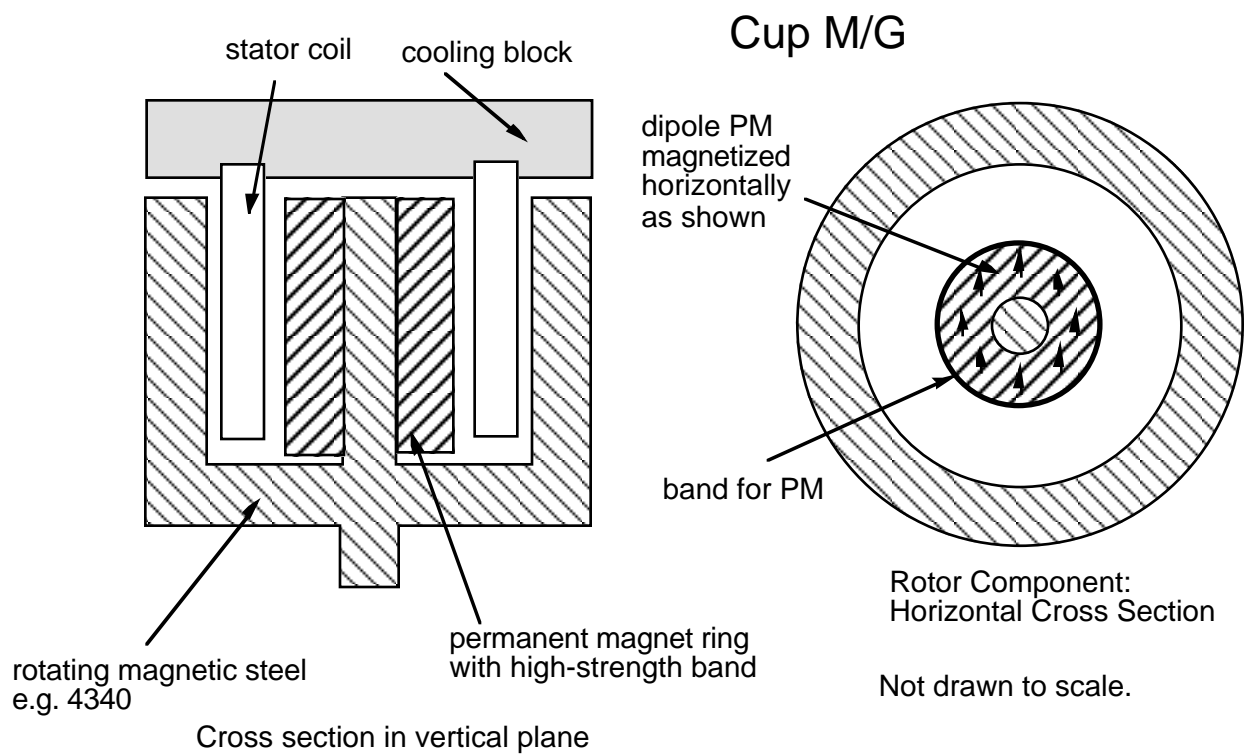
DOE Annual Peer Review Meeting

Washington, DC

July 18, 2002

FY02 Performance

1. Refined design for 100-kW cup-motor.
2. ANL participated in many aspects of system and component design and testing, including 4 weeks at Boeing, Seattle.
3. Analyzed spindown data and provided interpretation.
4. Developed thermal model of FES – used model to predict motor temperature.
5. Tested bearing with welded HTS.
6. ANL burst facility on standby.



Conventional M/G with toothless backiron

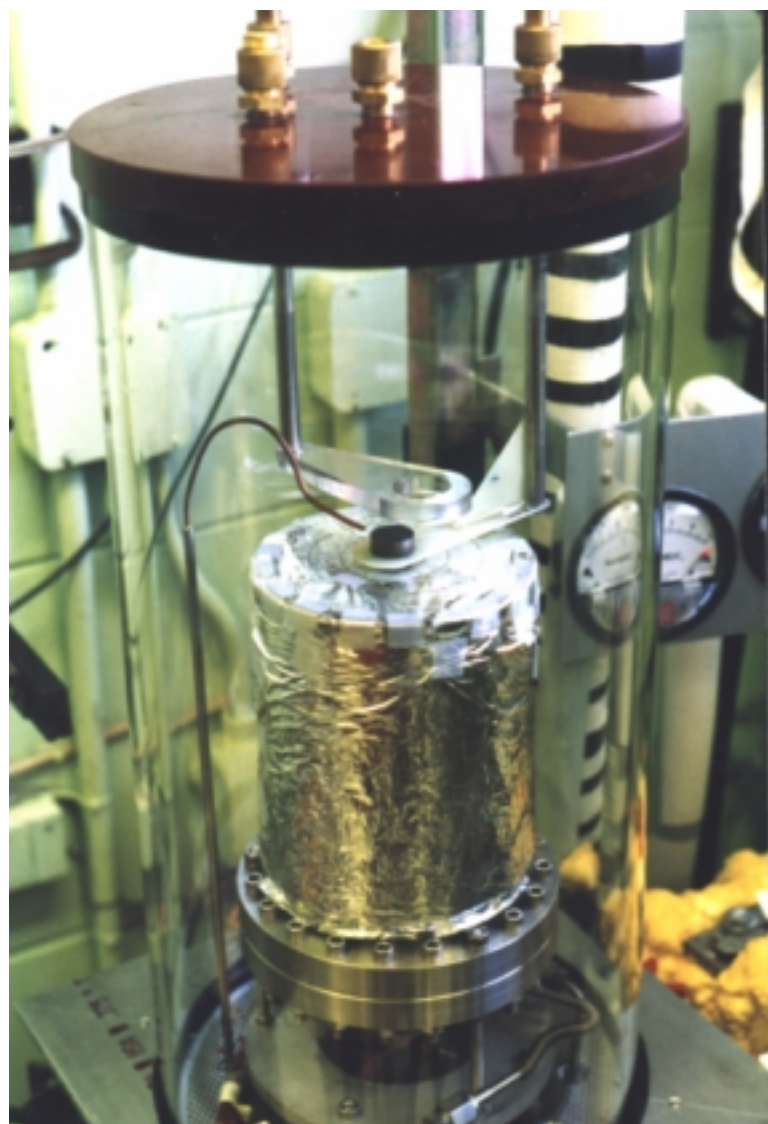
100-kW M/G Comparison

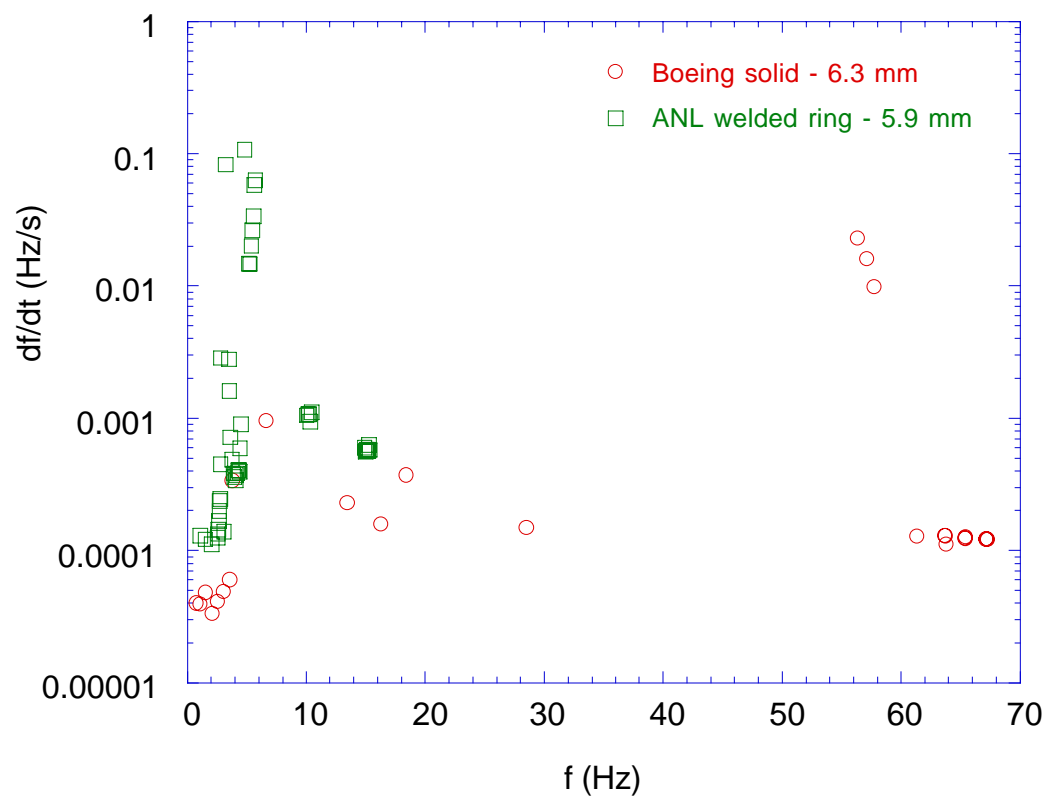
Conventional M/G with toothless stator backiron

1. PM on rotor acts on stator backiron to cause negative stiffness
2. Hysteresis loss in backiron

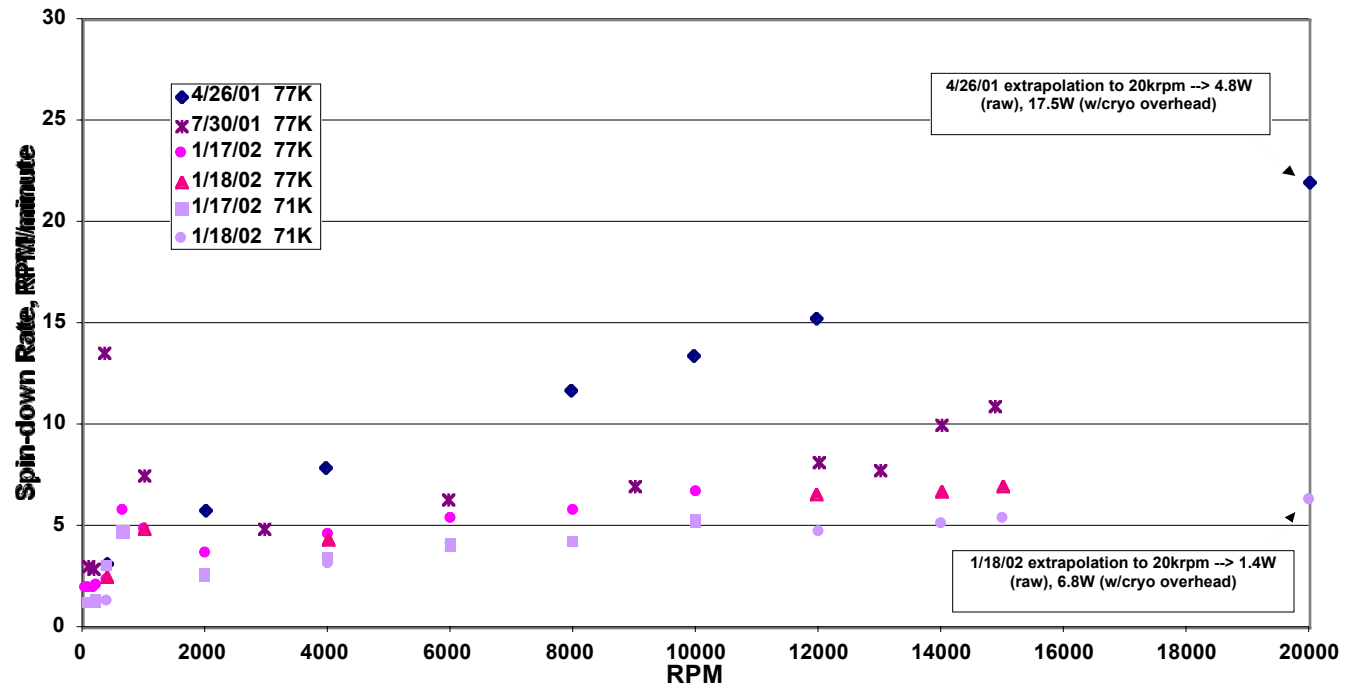
Cup M/G with rotating backiron

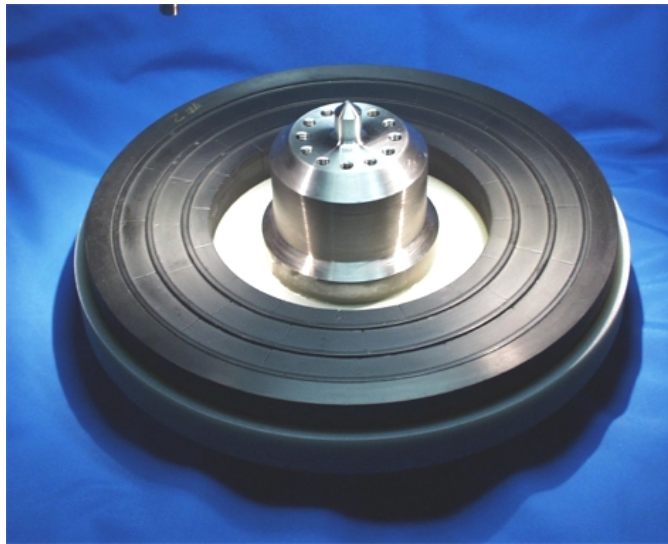
1. Stator coil acts on rotating backiron to cause negative stiffness— much smaller than conventional design
2. Must levitate additional weight of backiron and keep in from flying apart
3. Cooling and fatigue of cantilevered stator coil more difficult



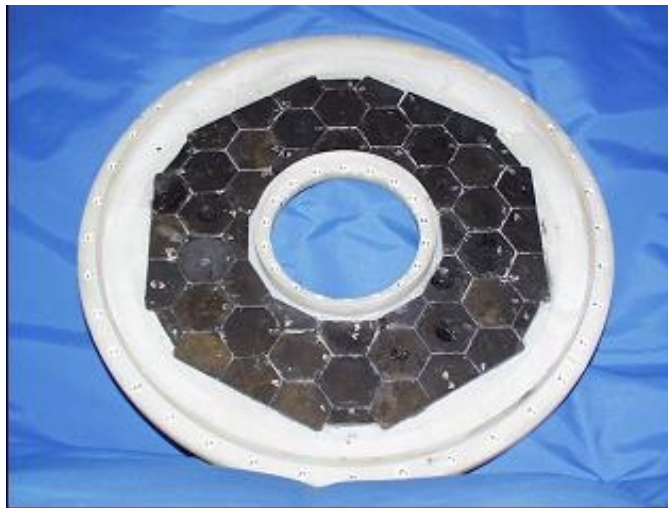


Spin-down of Boeing HTS Bearing - 4 mm Gap

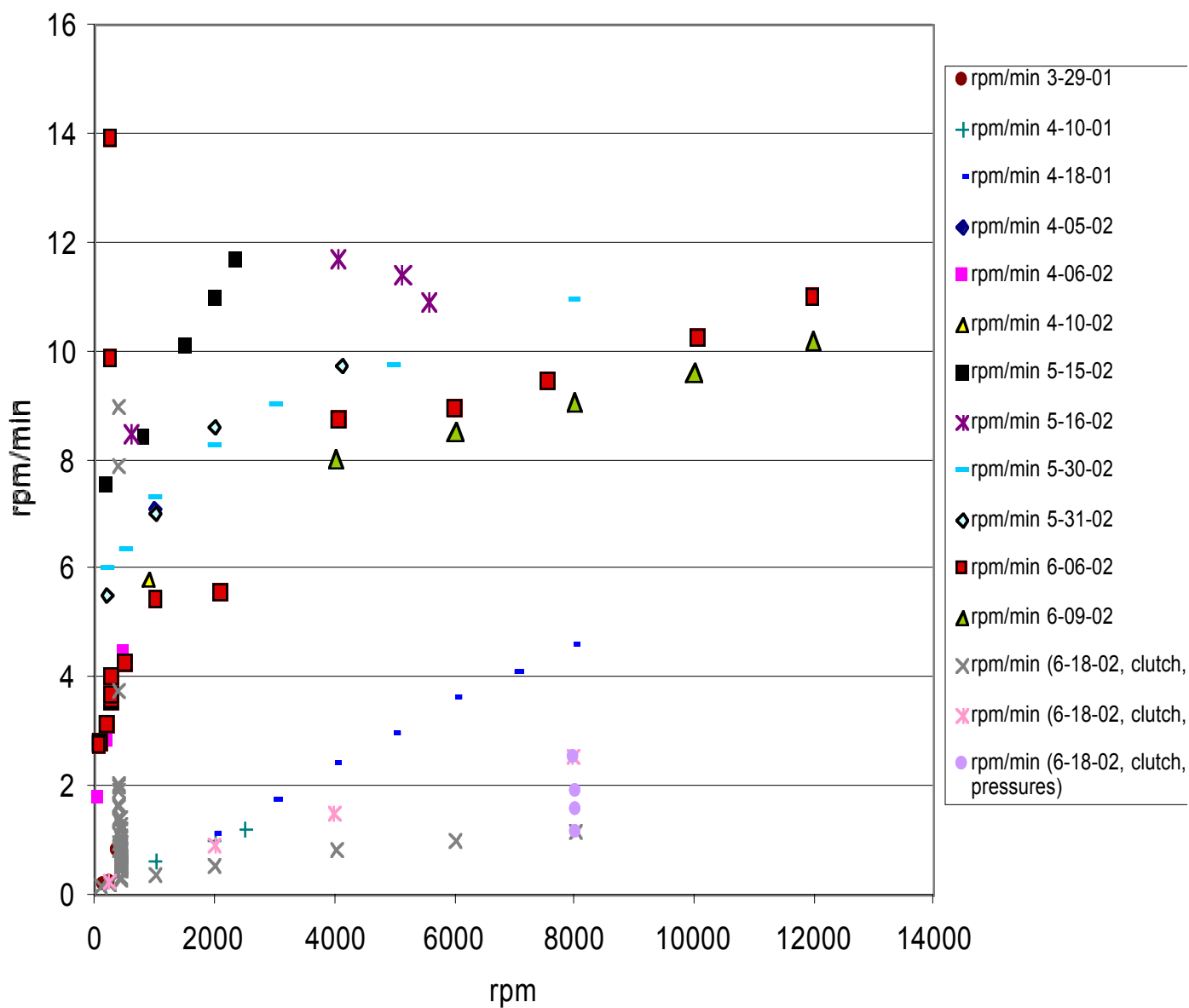


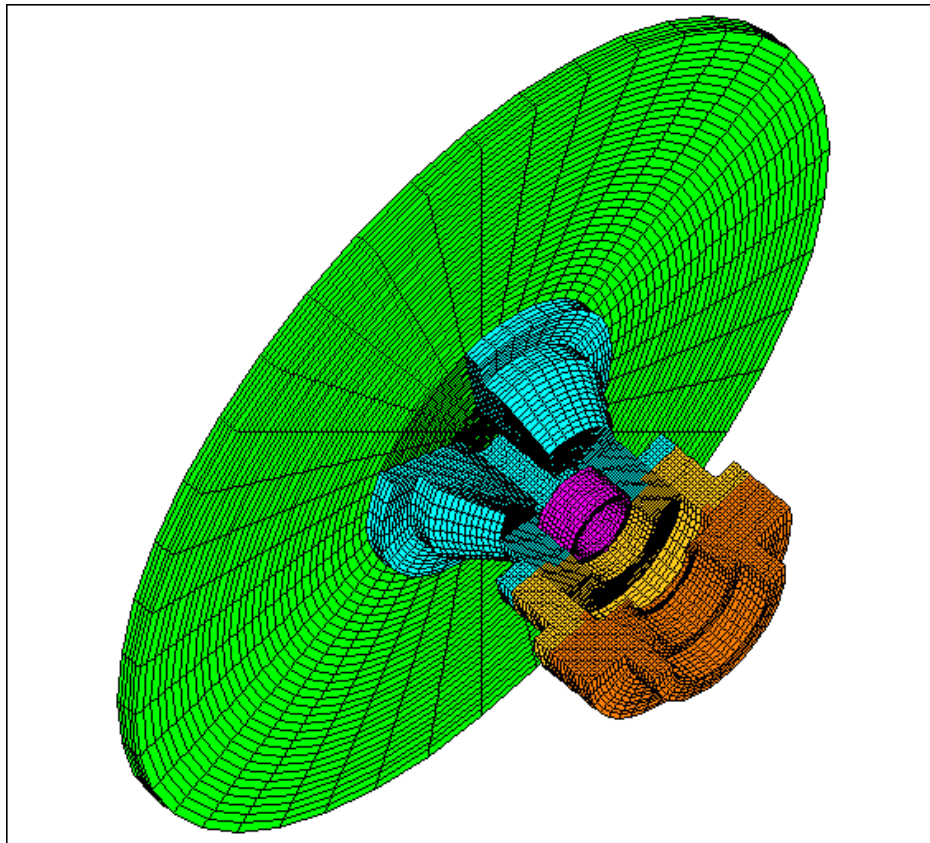


Magnet assembly for an HTS bearing, shown here installed on a bearing test rotor. This assembly is suitable for flywheels of up to several hundred pounds.



YBCO crystal array on underside of cryostat lid. Displacement of rotor magnets leads to large response currents in superconductors, passively restoring rotor position at any speed.





Motor Generator Housing



PROSTAR 3.10

01-JUL-02

VIEW

-.500

1.000

.500

ANGLE

.000

DISTANCE

22.918

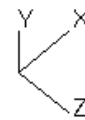
CENTER

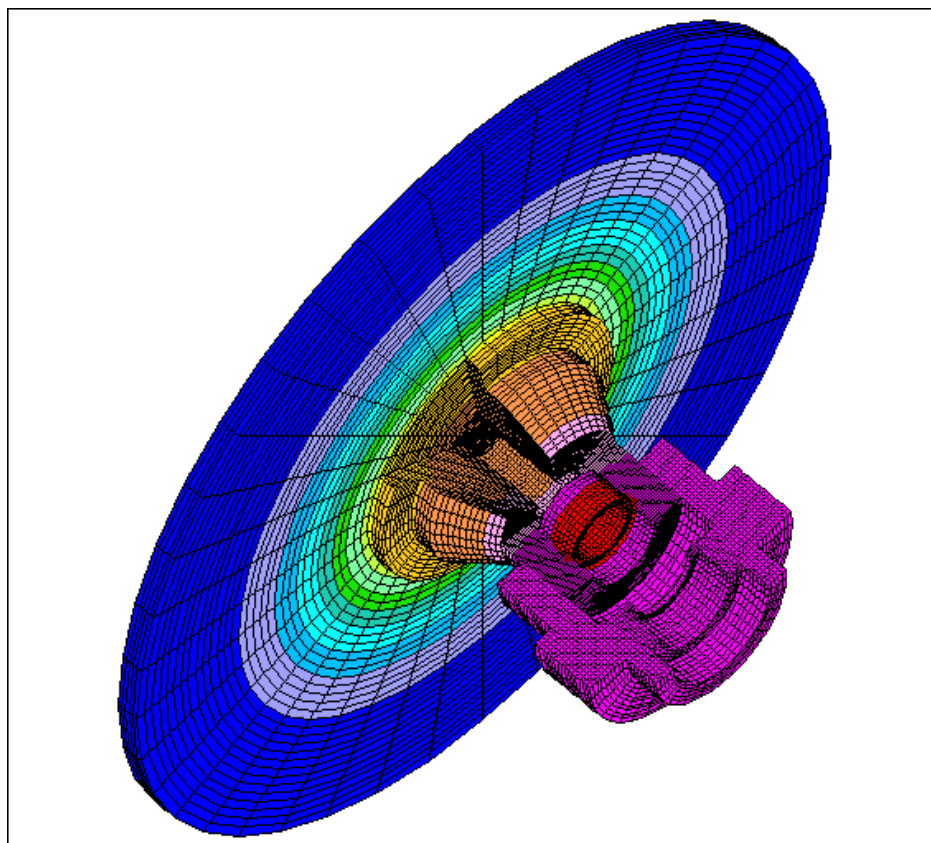
.000

.000

2.125

EHIDDEN PLOT





Motor Generator Housing (Aluminum)
Heat Source = 300 W

STAR
D
PROSTAR 3.10

21-MAY-02
TEMPERATURE
RELATIVE
CELSIUS
ITER = 12
LOCAL MX= 69.36
LOCAL MN= 35.06

	69.36
	66.91
	64.46
	62.01
	59.56
	57.11
	54.66
	52.21
	49.76
	47.31
	44.86
	42.41
	39.96
	37.51
	35.06



Door and Entryway to “50-kWh” Burst Containment Room



Role of Argonne National Lab in FES Project



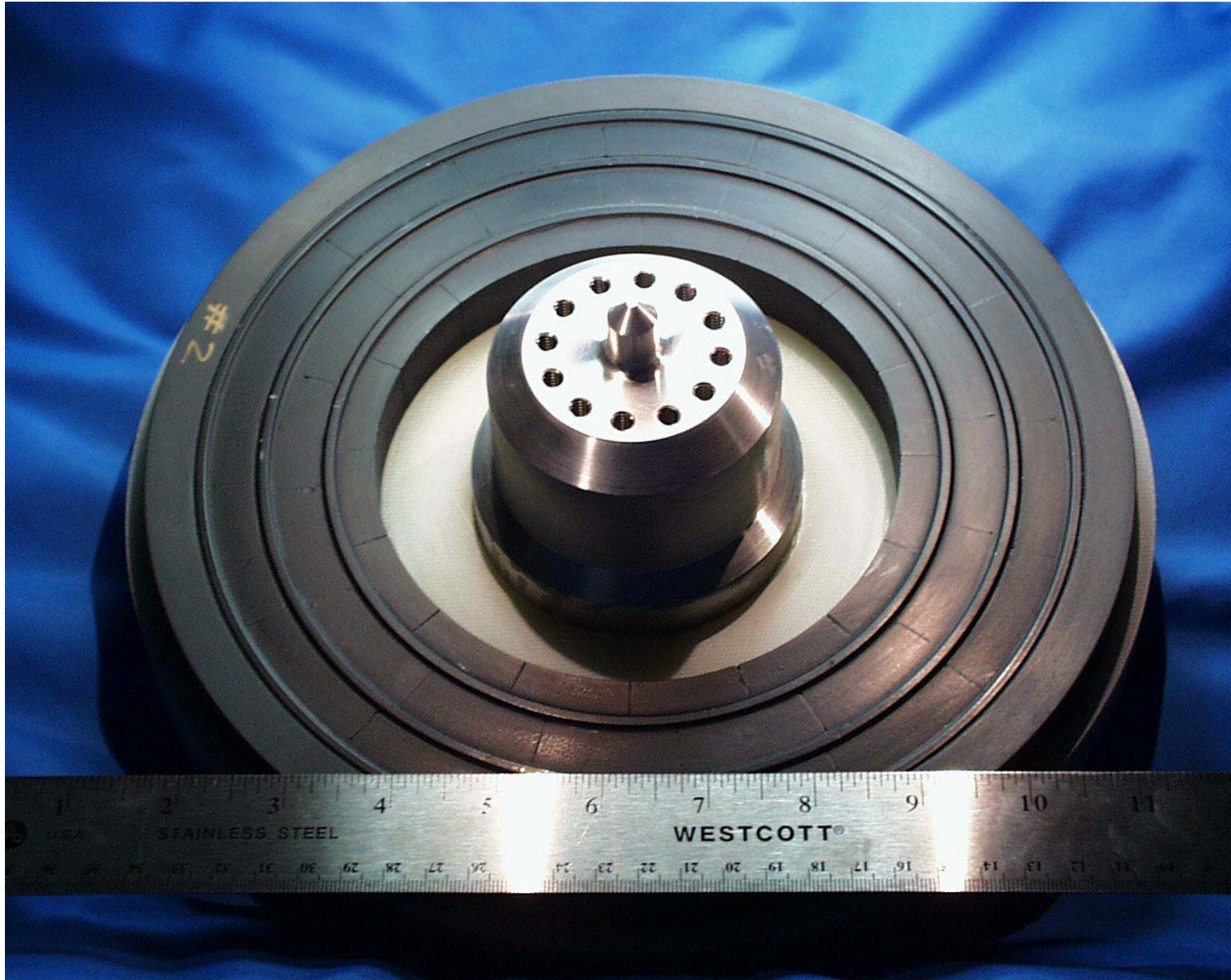
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- Provide general consultation on design of system and components, based on ANL's previous experience with these types of devices
- Argonne personnel participated in system requirements and preliminary design review
- Explore alternative M/G topologies for the 100 kW system
- An electromagnetic clutch for bearing tests was designed and fabricated at ANL - is now a key part of bearing test
- Assist in the analysis of HTS bearing performance
 - Understanding of loss mechanisms and support for improvement
 - Cryogenic expertise and lab support have been invaluable
- Thermal issues are coming to the fore (rotor, cryogenics) – ANL to help explore/model behavior, leading to loss reductions.

10 kWh Flywheel Bearing Rotor



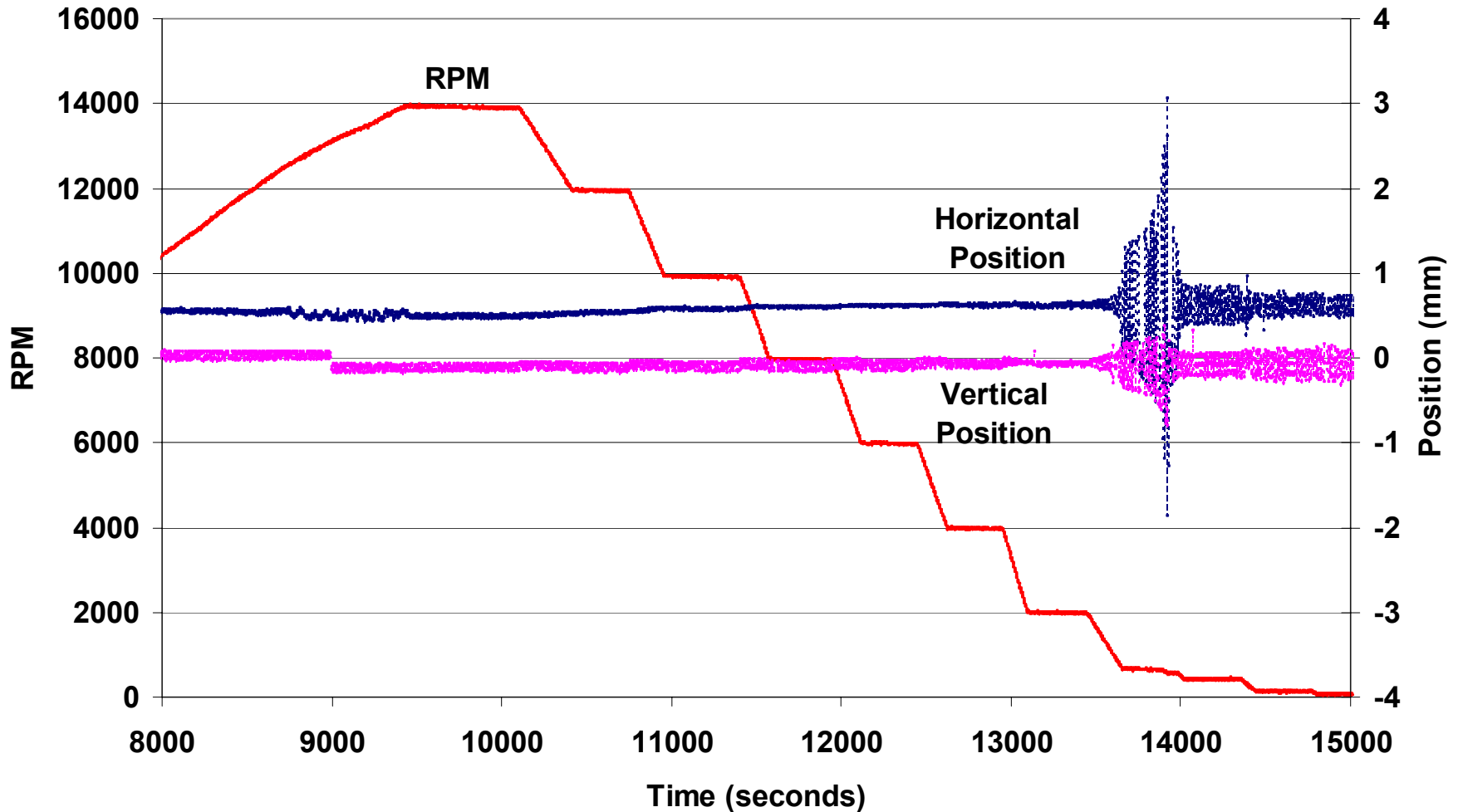
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Jan 29 2002 Bearing Test to 14,000 rpm



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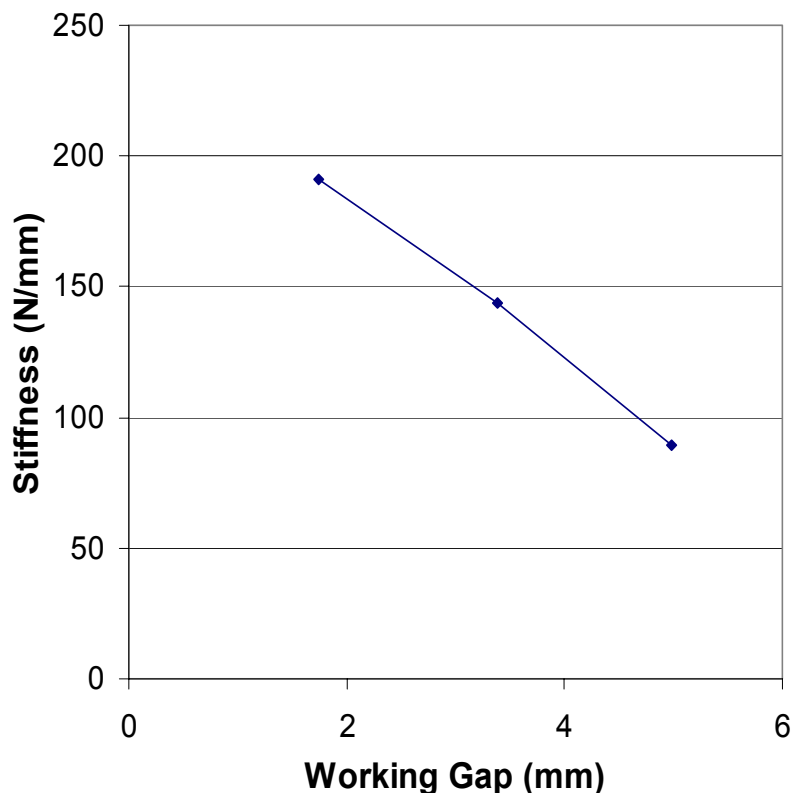


Dynamic Characteristics of Bearing

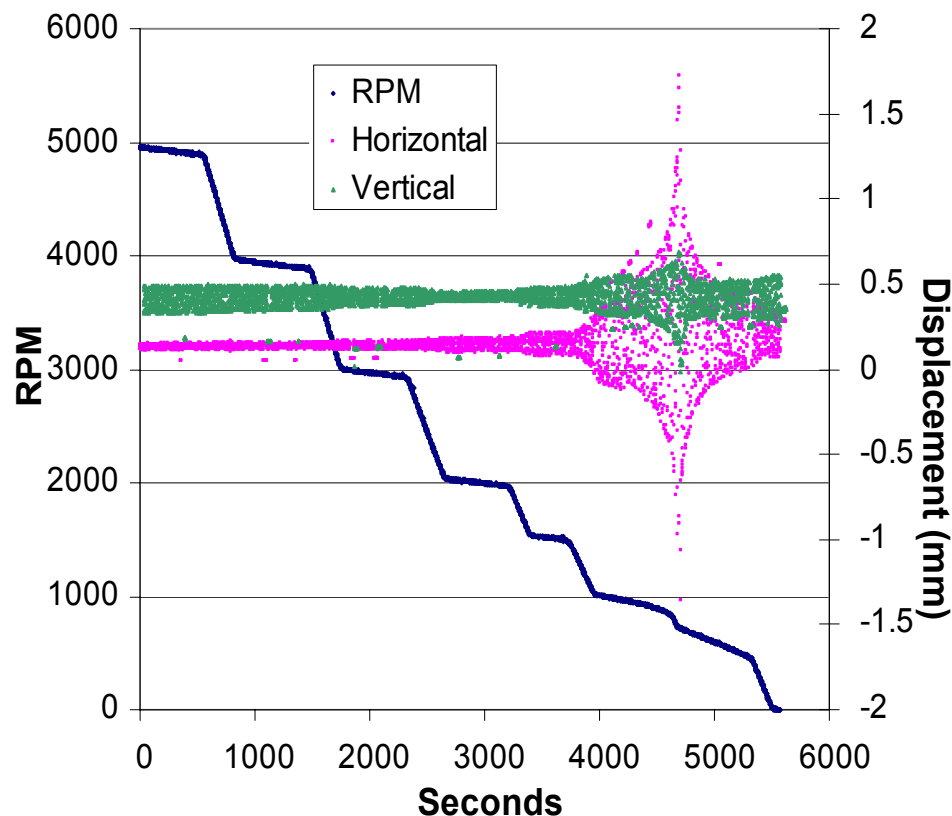


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Stiffness vs. Magnet/Cryostat Gap



Effect of Low Damping at Critical Speed



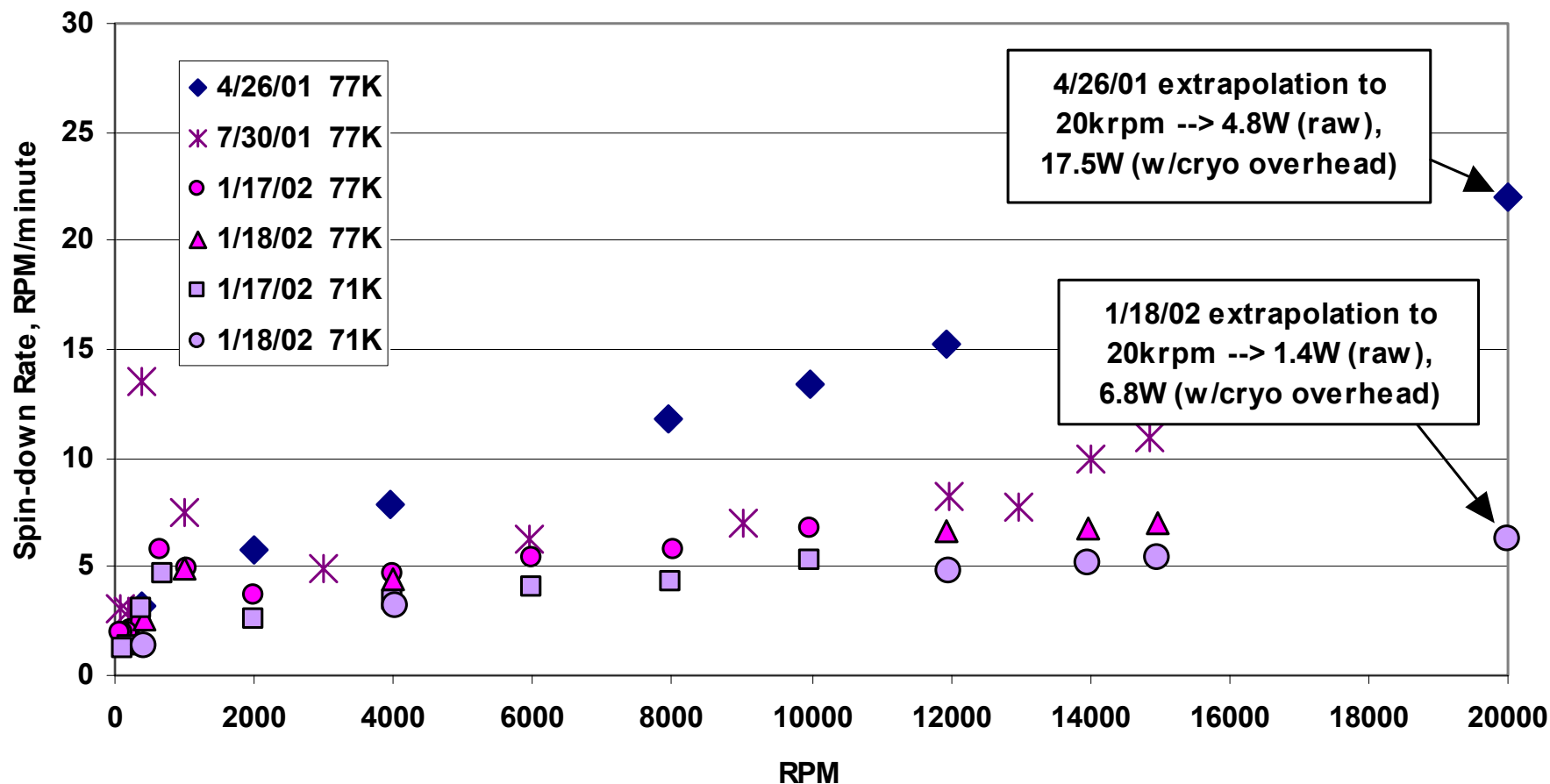
- Bearing stiffness is good, with low damping as expected
- Flywheel may need auxiliary damping at some speeds

Jan '02 Bearing Tests: 3X Loss Reduction



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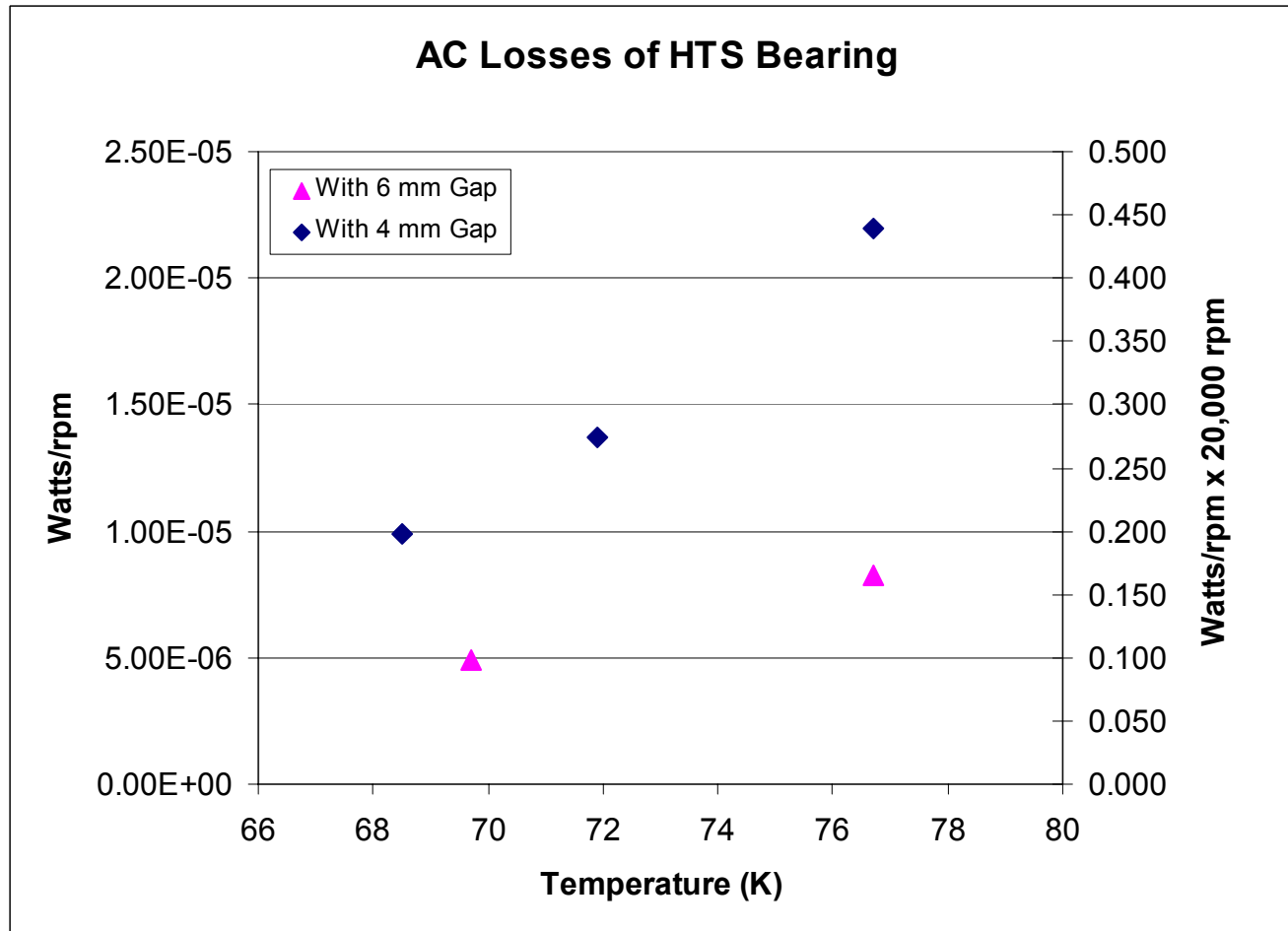
- Closed-cycle System Yields AC Losses < 1 Watt



Bearing AC Loss vs. Temperature



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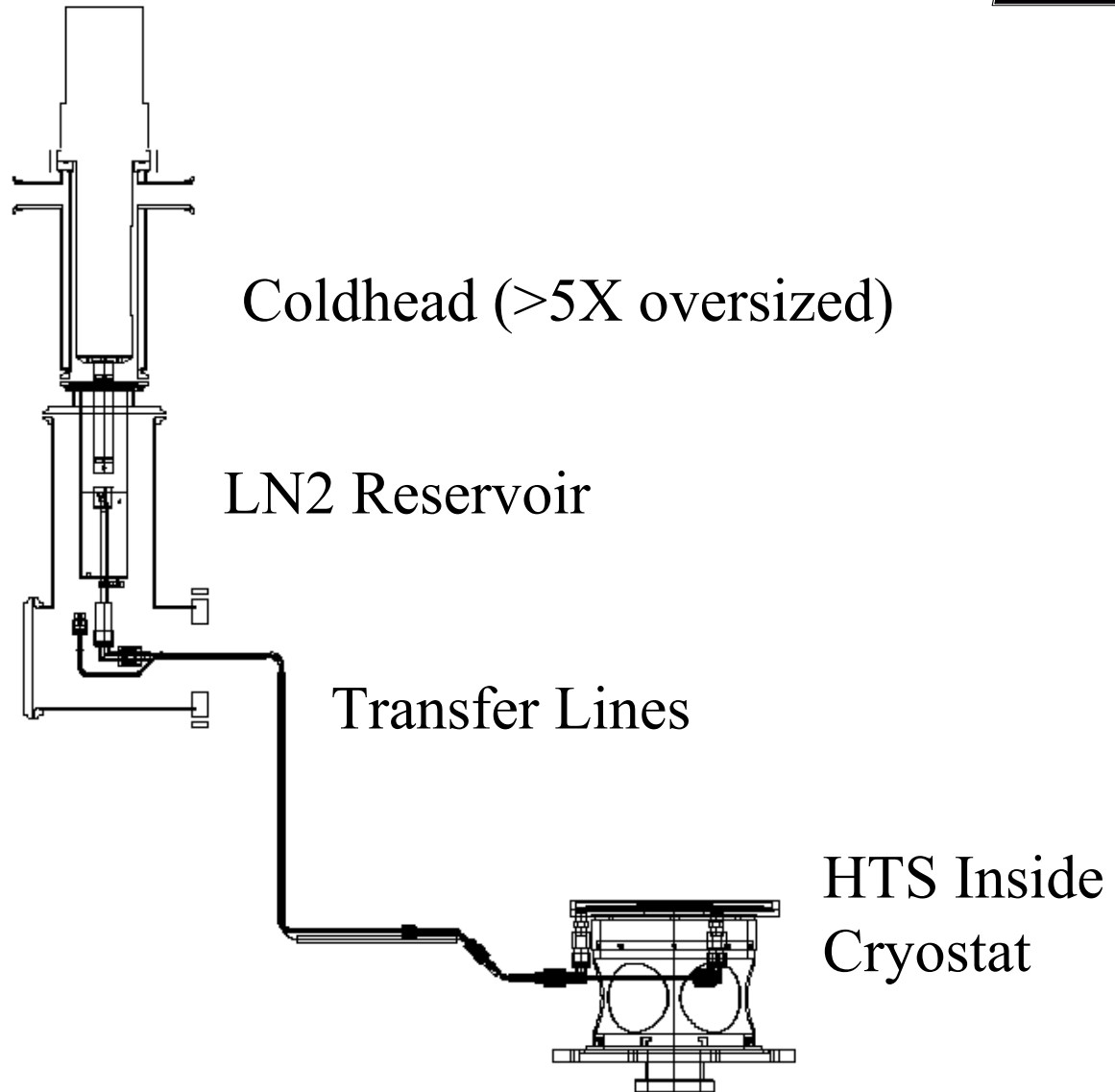


- ❖ Operation at reduced temperature enabled by Mesoscopic passive flow system and loaned ANL cooler

Cryogenics Experimental Layout



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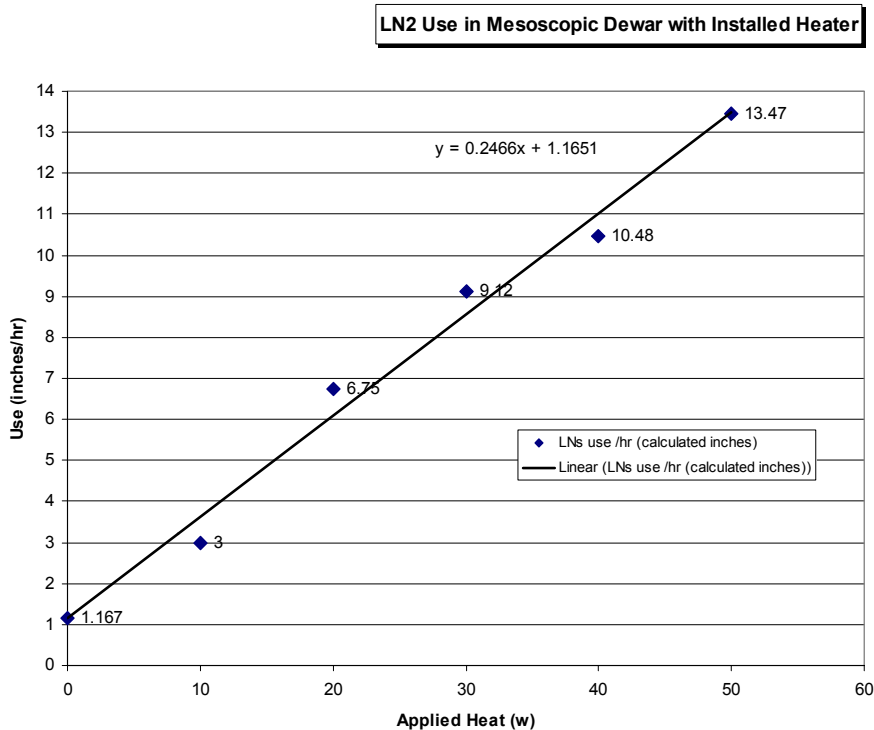


Cryogenic Losses



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LN Use Measurement



Parasitic losses

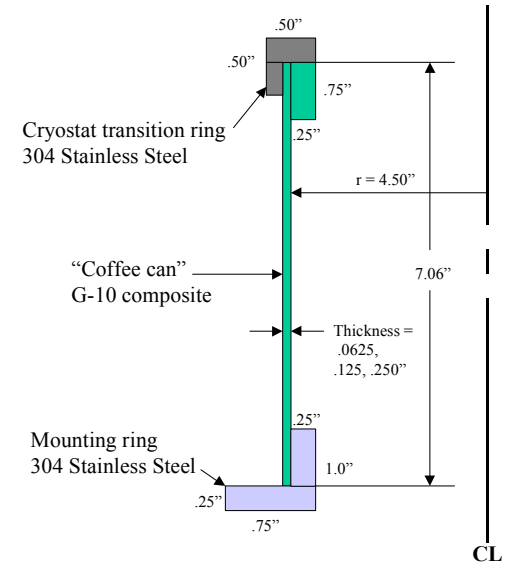
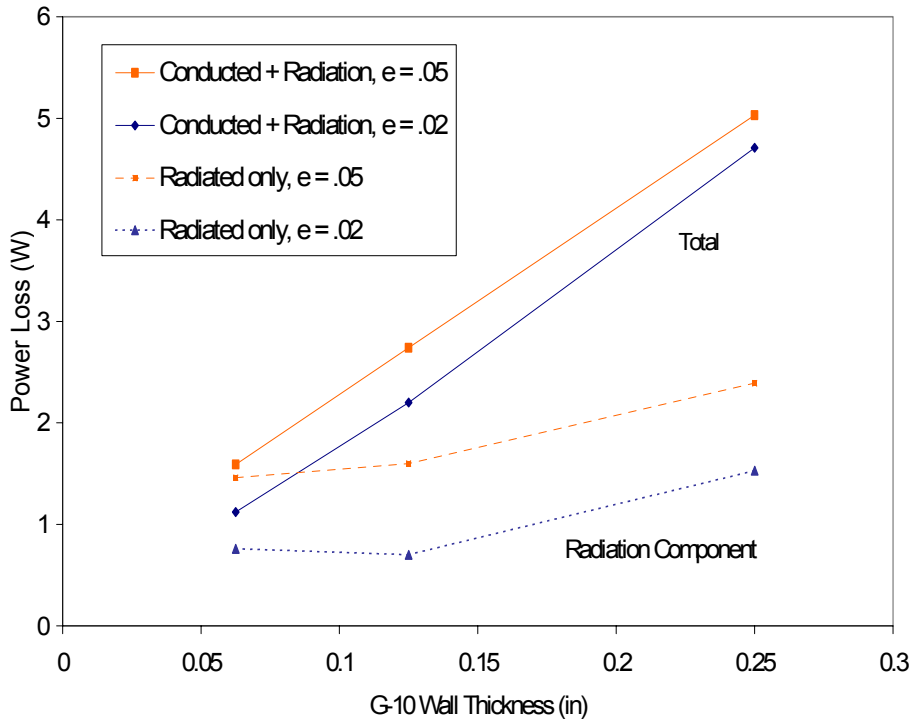
Cryostat radiation	1.5 Watts
Reservoir conduction	4.5
Transfer lines	6
Cryostat supports	11
Total	23 Watts

Cryogenic Load Reduction



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- Thermal model of cryostat support can shows parasitic loss can be drastically reduced



Old

New

HTS Bearing – Some Conclusions and Status



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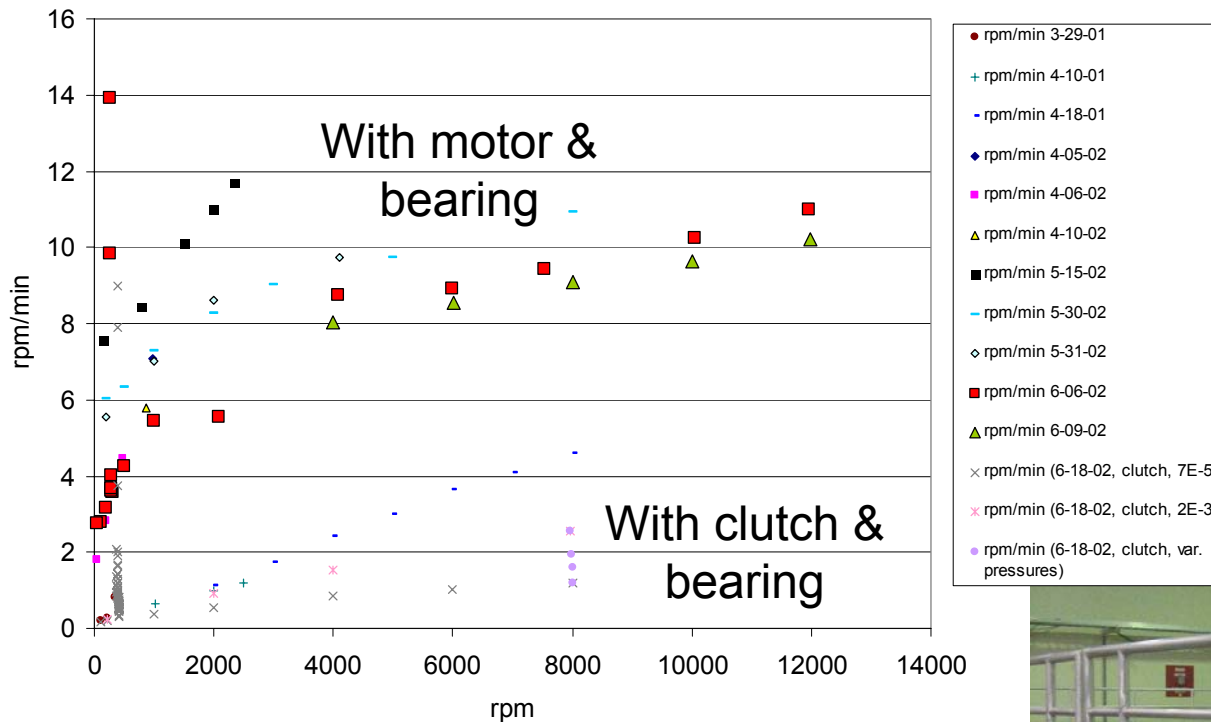
- Bearing stiffness of 72 – 150 N/mm meets original design expectations and should be adequate for 10 kWh flywheel.
- If AC loss is as described previously, its component will contribute 14 – 17% of the bearing raw power loss at 20,000 rpm. This will be under a watt.
- Bearing net power loss (with refrigeration) *should* thus be < 10 Watts. In a 10 kWh flywheel, 10 W \rightarrow 0.1%/hour loss of stored energy.
- Actual bearing loss in a flywheel will be somewhat greater due to vibrational motion of full rotor system (balance and tolerance issue). Testing is planned.
- Total cryogenic load will also include conducted and radiated heat. Now 25 - 30 W. For the UPS flywheel system the cooler is designed for 30 W total at 72K (normal) with 60 W capacity for cooldown.

Bearing and Motor Loss Analysis

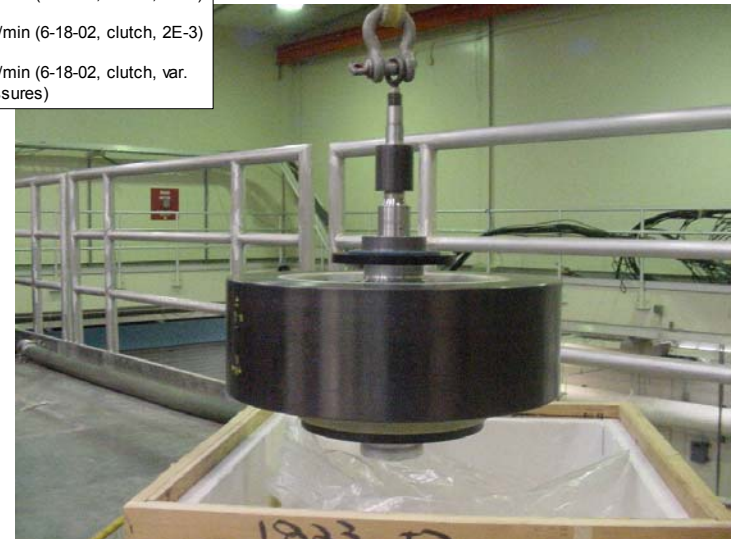


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- Loss Contributors Studied on 1 kWh ESS Flywheel



1 kWh ESS/Sandia Flywheel →



1 kWh Flywheel Installation in Test Chamber



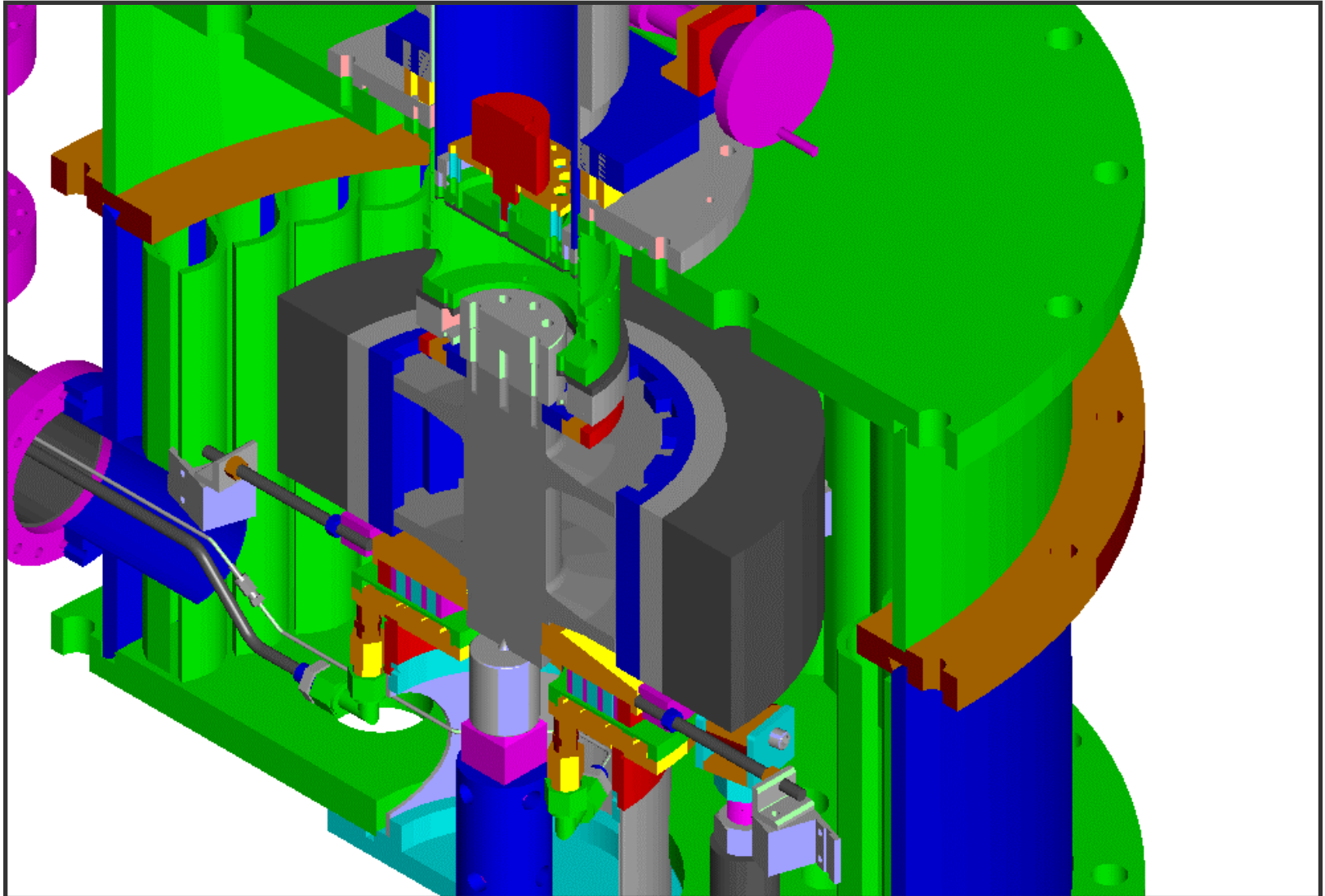
PHANTOM WORKS



Cutaway View in Test Chamber



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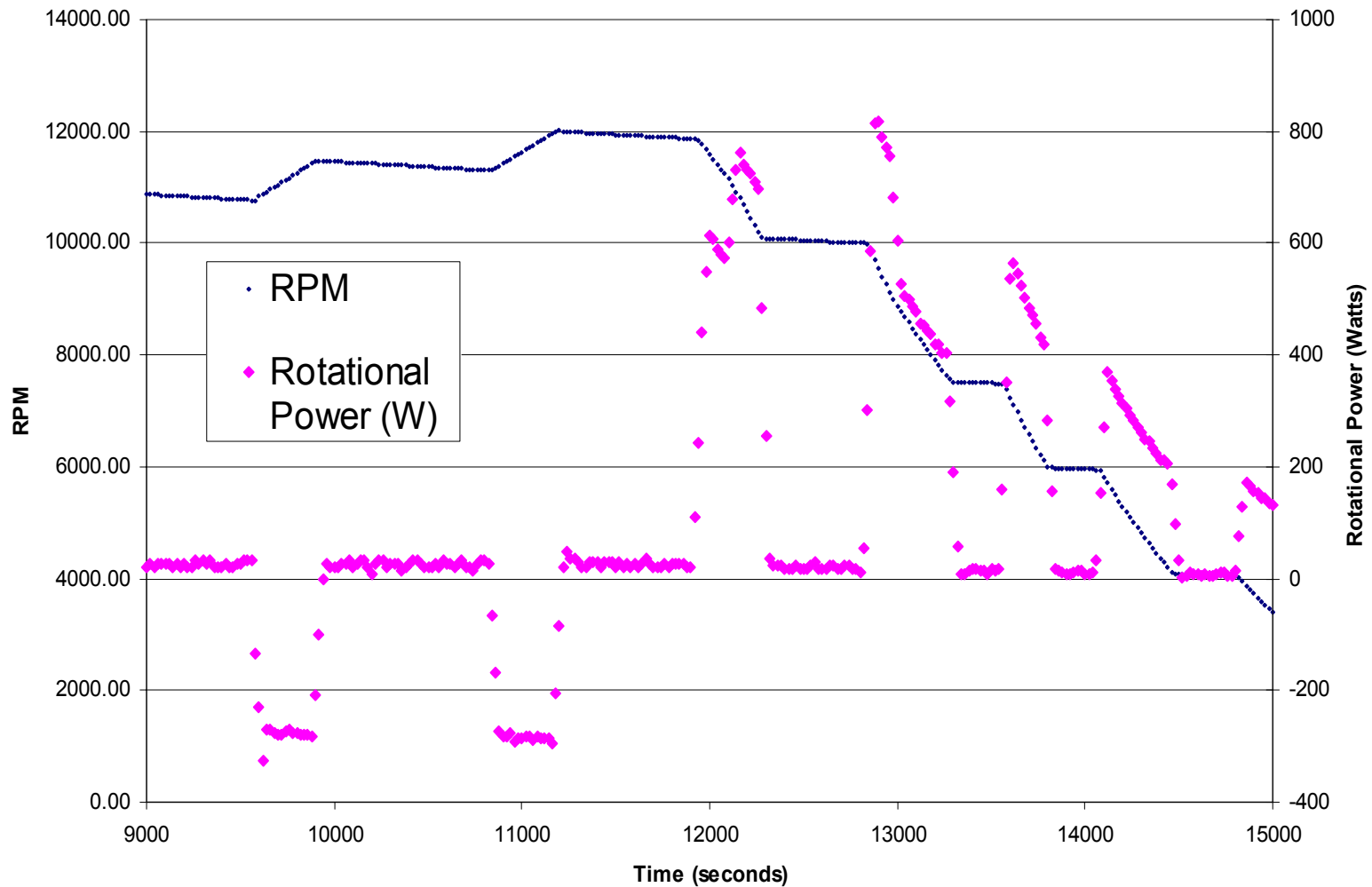


1 kWh Wheel with M/G – Power Out



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Power Profile 06 June 02

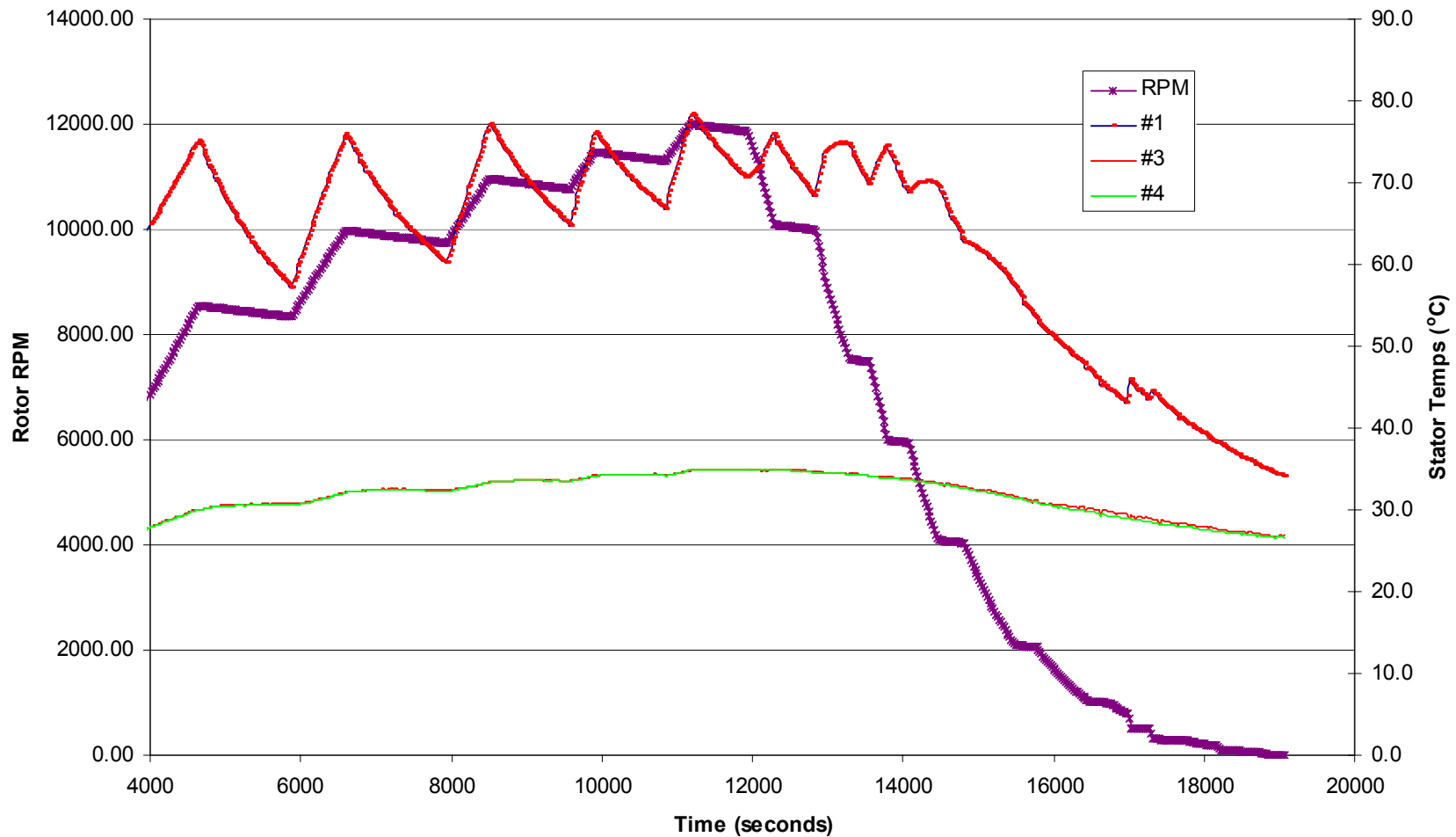


1 kWh Flywheel Speed & Motor Temperature



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Stator temps and RPM 06 June 02

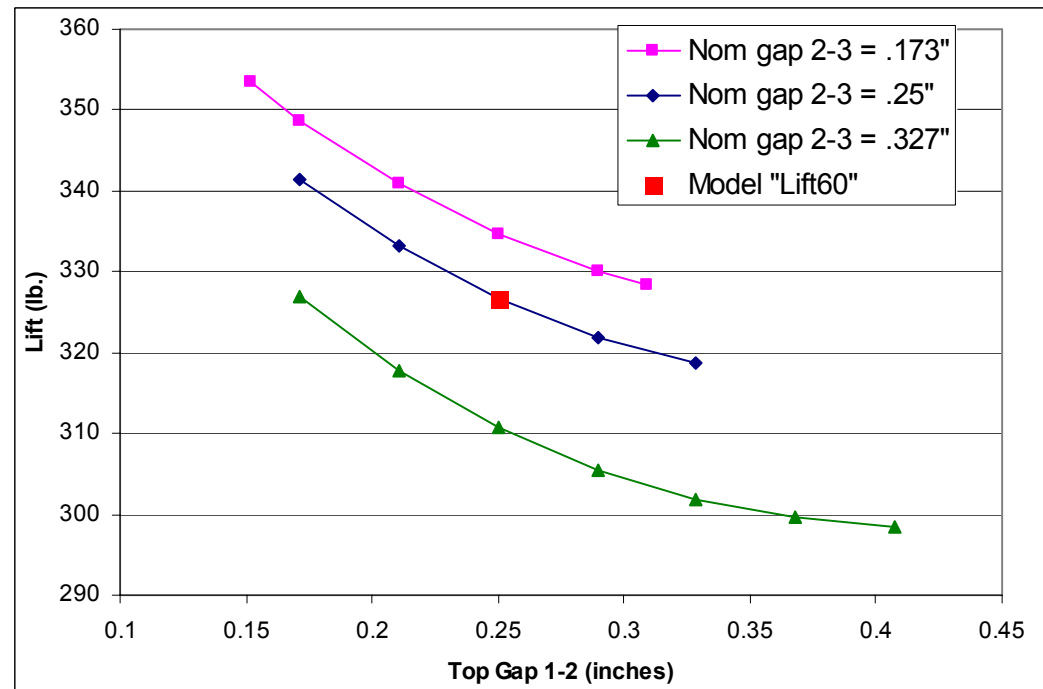


Validation of Push-Pull Lift Design



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- Design refinement and load-cell test data are in excellent agreement
- Design gives negative stiffness of approx. 25 N/mm, << HTS bearing at 150 N/mm



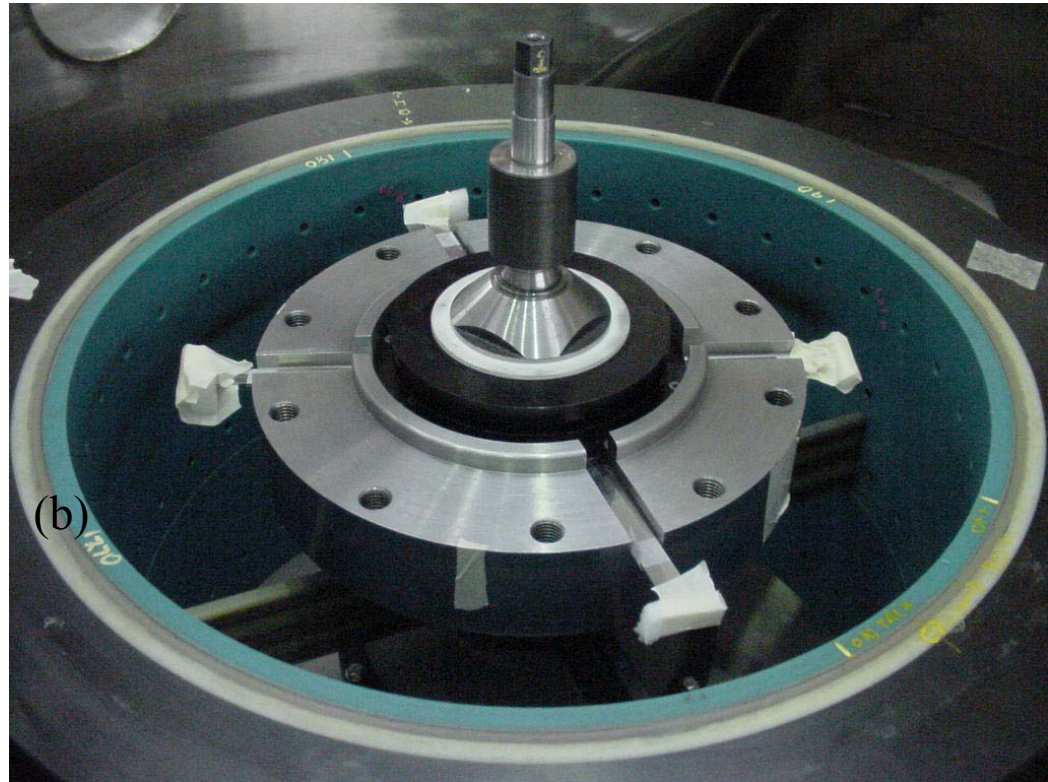
Assembly of Lift Magnet Structure



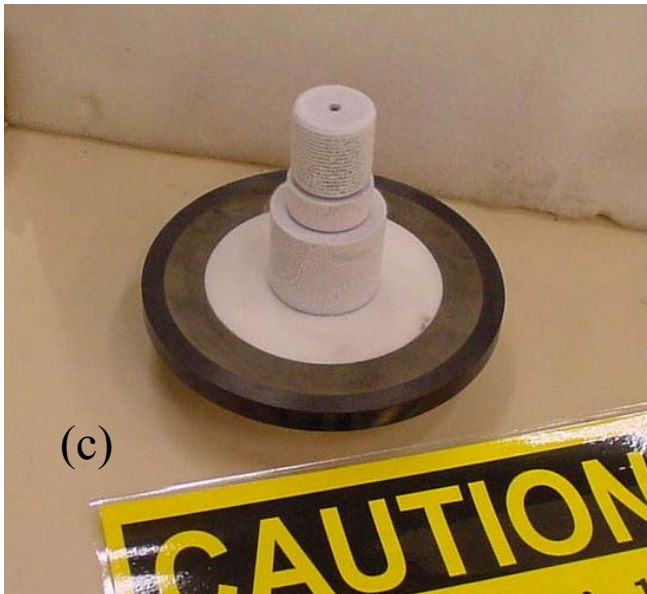
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(a)



(b)



(c)

- (a) Upper Touchdown Bearing and Lift Magnet
- (b) Partial Assembly with Rotor
- (c) Lift Magnet Rotor and M/G Rotor

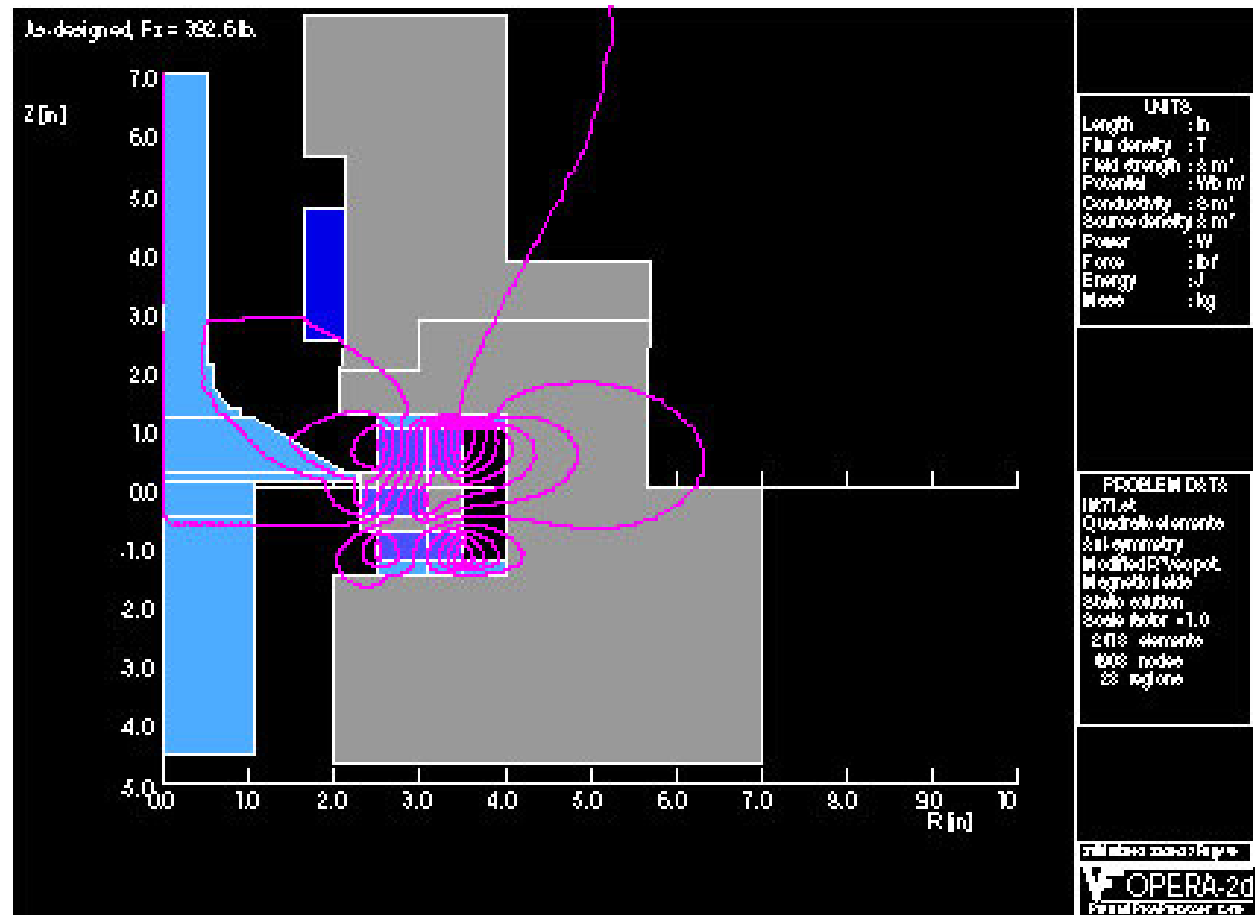
Housing Material Switch, Round 1



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- Original drawings based on non-magnetic housings
- In-course corrections resolved magnetic lift problem

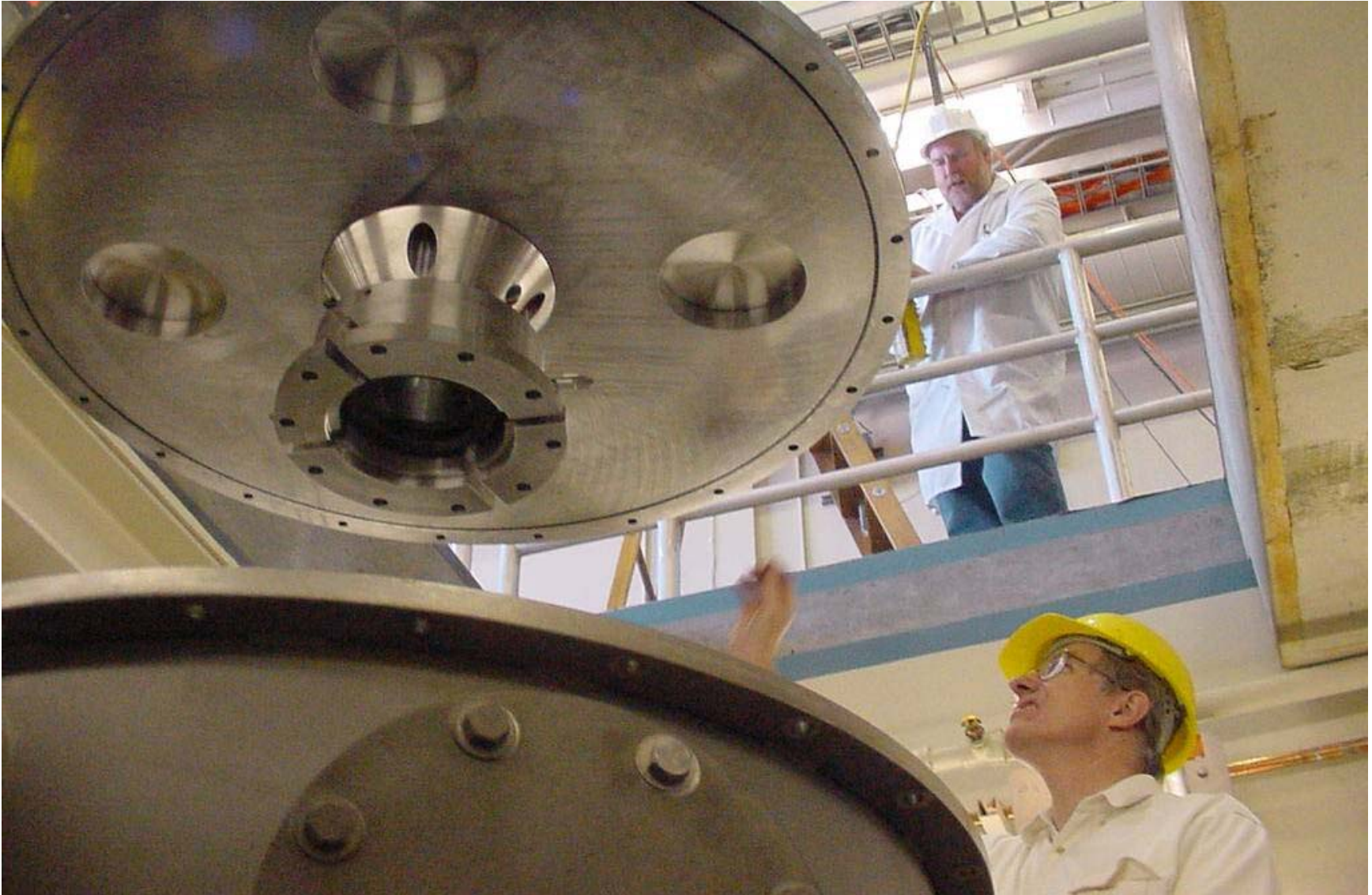
FEA of stator housings and upper shaft



Watch those fingers . . .



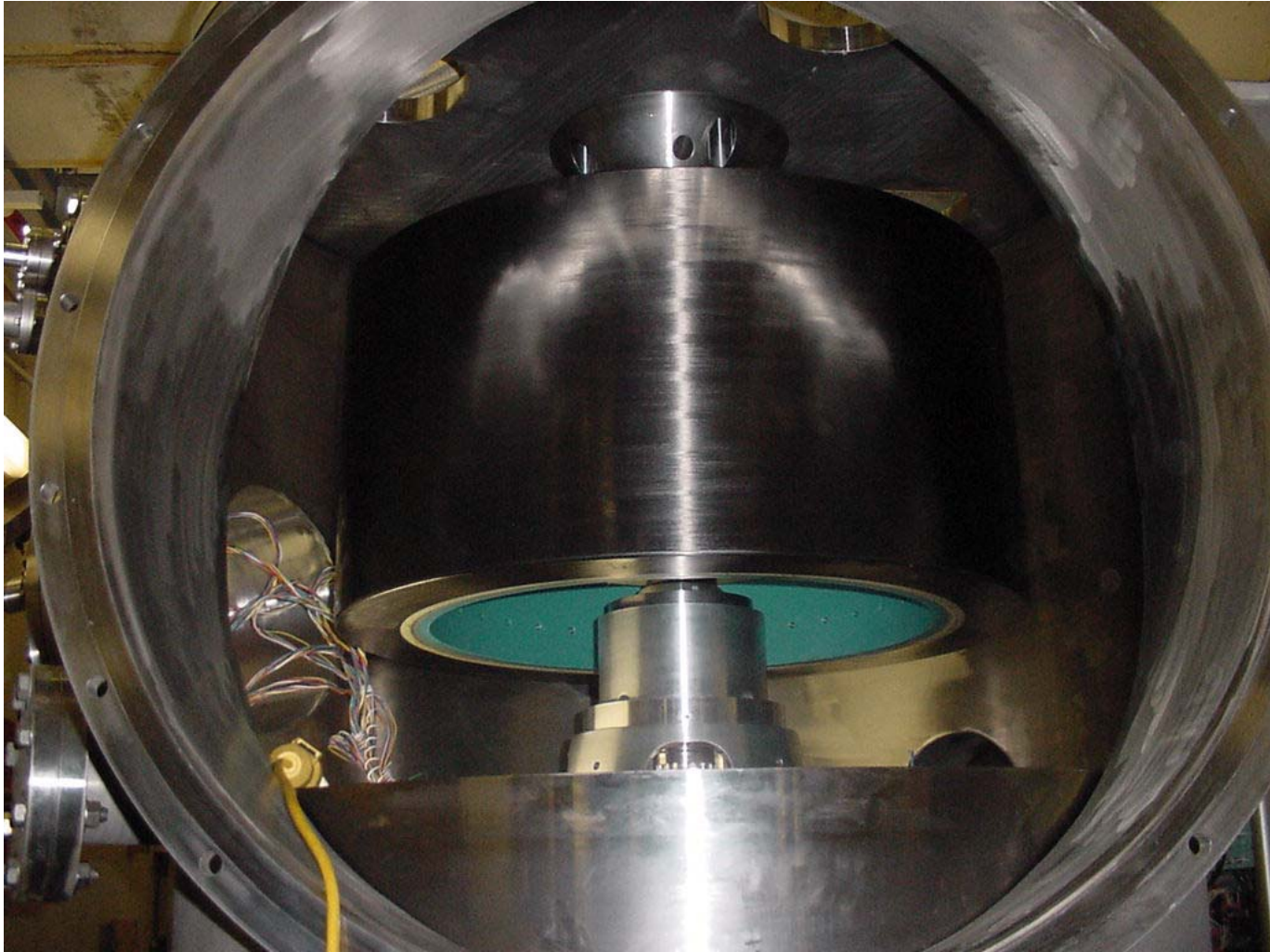
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10kWh Flywheel in Test Chamber



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Flywheel Diameter = 33"

Final Assembly



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10 kWh and chamber

Cryostat and lines



Boeing Test Area Analysis Support



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“Notes on Pit Safety at the Boeing Flywheel Experimental Facility”

John Hull – 1/14/02

“The following notes are recommendations for the safety aspect of the pit at the Boeing Southpark facility an improvement over the blocks used at ANL . . . exceedingly conservative . . . should be monitored by a video camera . . .



10 kWh Rotor Dynamic Testing



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Rotor Assembly



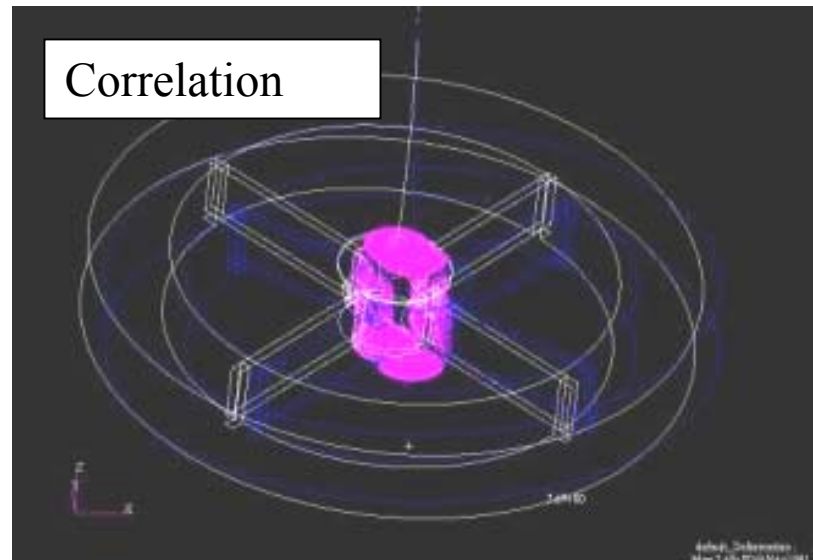
Spin Testing



Shaker Testing



Correlation

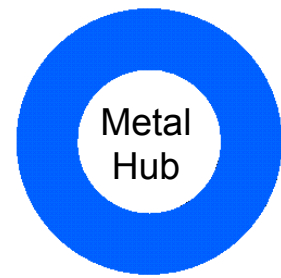
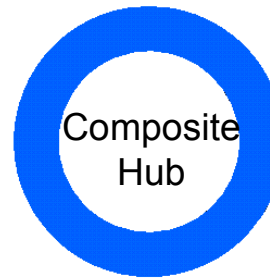
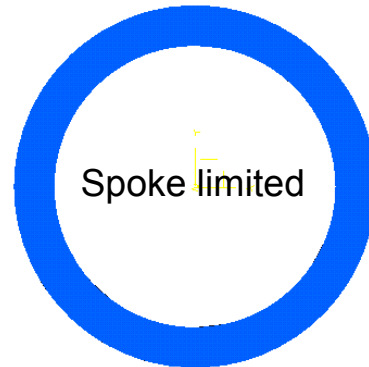


Evolution of Rotor Design



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- New UPS designs permit more & cheaper hub options



Design Feature	LL Prototype	UPS Option 1	UPS Option 2
Total Energy	10 kWh	4.7 kWh	4.7 kWh
Speed	20,000 rpm	24,000 rpm	24,000 rpm
Power	3-10 kw	100 kw	100 kw
Duration	3 hours	1 minute	1 minute
OD	31.57 in	23.62 in	23.2 in
ID	24.5 in	15.74 in	12.5 in
% Growth of ID	0.8%	0.71%	0.48%

100 kW / 4.5 kWh HTS Bearing



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- 9" O.D. / 4-pole magnet assembly and HTS should give adequate loss, stiffness for 100 kW system
- Confinement hoop and "salad bowl" on 3 kW / 10 kWh system are not capable of withstanding 24,000 rpm operation (tip speed at 9" O.D. = 290 m/s).
- Similar magnet structures in Japan have reported these tip speeds (but with small safety margin).

Final magnet design to be close to current design, but with changes to accommodate speed, loading

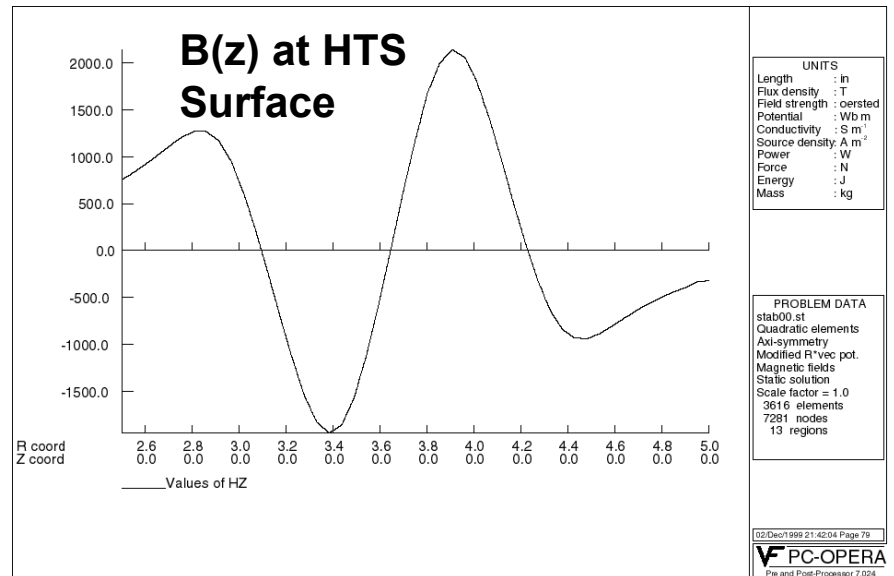
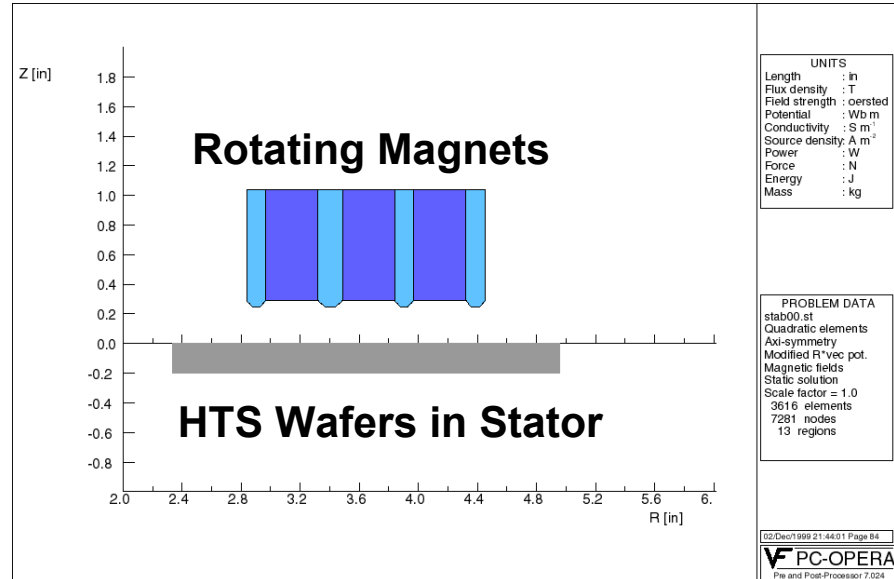
- Modest evolutions expected for cold stage and lift magnets

FEA of 4-Pole HTS Stability Bearing



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- Boeing and ANL models were used together for design of first prototype.
 - Gradient
 - Diamagnetic
- Approach will be carried forward for 100 kW system



Boeing HTS Bearing Scaling: Progress and Projections



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Test Article	Weight (approx.)	# Magnet Rings	Diameter	Speed (rpm)
Bearing (1996)	5 lb.	1	6"	5,000 tested
Bearing (2000-2002)	20 lb.	3	9"	15,000 tested 24,000 design
1 kWh Flywheel (2001-2002)	100 lb.	3	9"	12,000 tested 24,000 design
10 kWh Flywheel (2001-2002)	400 lb.	3	9"	12-15,000 tested 20,000 design
35+ kWh Flywheel (future)	1500-2000 lb.	4	12" (approx.)	12-16,000 design

- ❖ Module sizes to 50 kWh appear practical with current bearing configuration
- ❖ Larger modules likely to use multi-plane or axial configurations

HTS Bearing Team



PHANTOM WORKS



... after recording first sub-77K bearing spins at Boeing, Jan. 2002

Conclusions

1. Boeing and ANL (and with other project team members) have worked well together to keep the SPI project moving in a timely manner toward a successful demonstration of a 10-kWh flywheel energy system using HTS bearings.
2. HTS bearing losses meet the project requirements. Measured losses are qualitatively understood and further improvements to reduce losses are possible.
3. A thermal model of the flywheel system has been established and is expected to contribute to future design improvements.